INTEGRATED REAL-TIME CONTROL FOR ADVANCED STEADY STATE SCENARIOS AND APPLICATIONS TO BURNING PLASMAS

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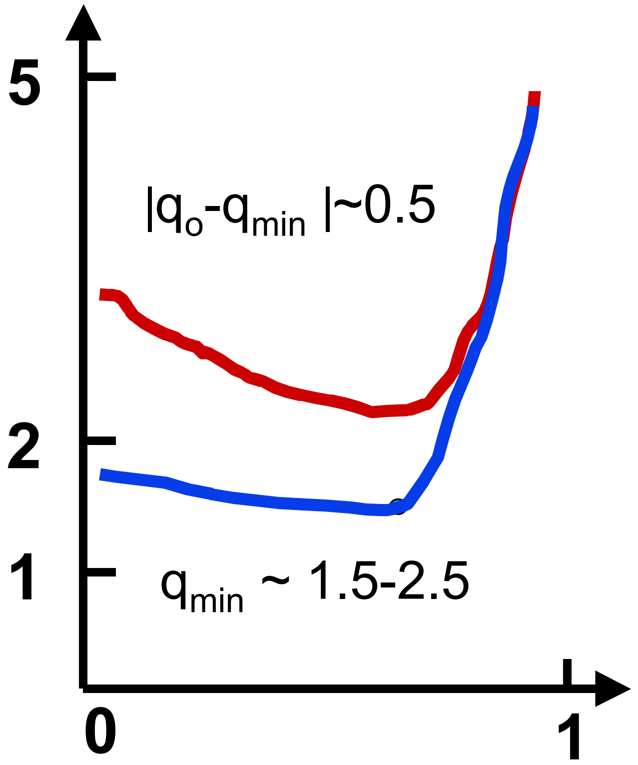
OUTLINE

- ➔ Burning plasma issues, actuators, sensors, non-linear couplings ...)
- ➔ Need for integrated profile control in AT burning plasmas
- ➔ Initial experiments on integrated profile control on JET
- ➔ The multiple time scale approach under development on JET
- ➔ Integration of profiles and flux control with the
  JET eXtreme Shape Controller for non-inductive operation
- ➔ Role of JET for developing AT burning plasma integrated control

Requirements for ITER advanced tokamak (AT) operation

ITER advanced scenario = steady-state operation at Q ~ 5 (P_α~P_{add}) with full non-inductive current drive (ITB + high bootstrap)

Requirements for ITER AT operation:



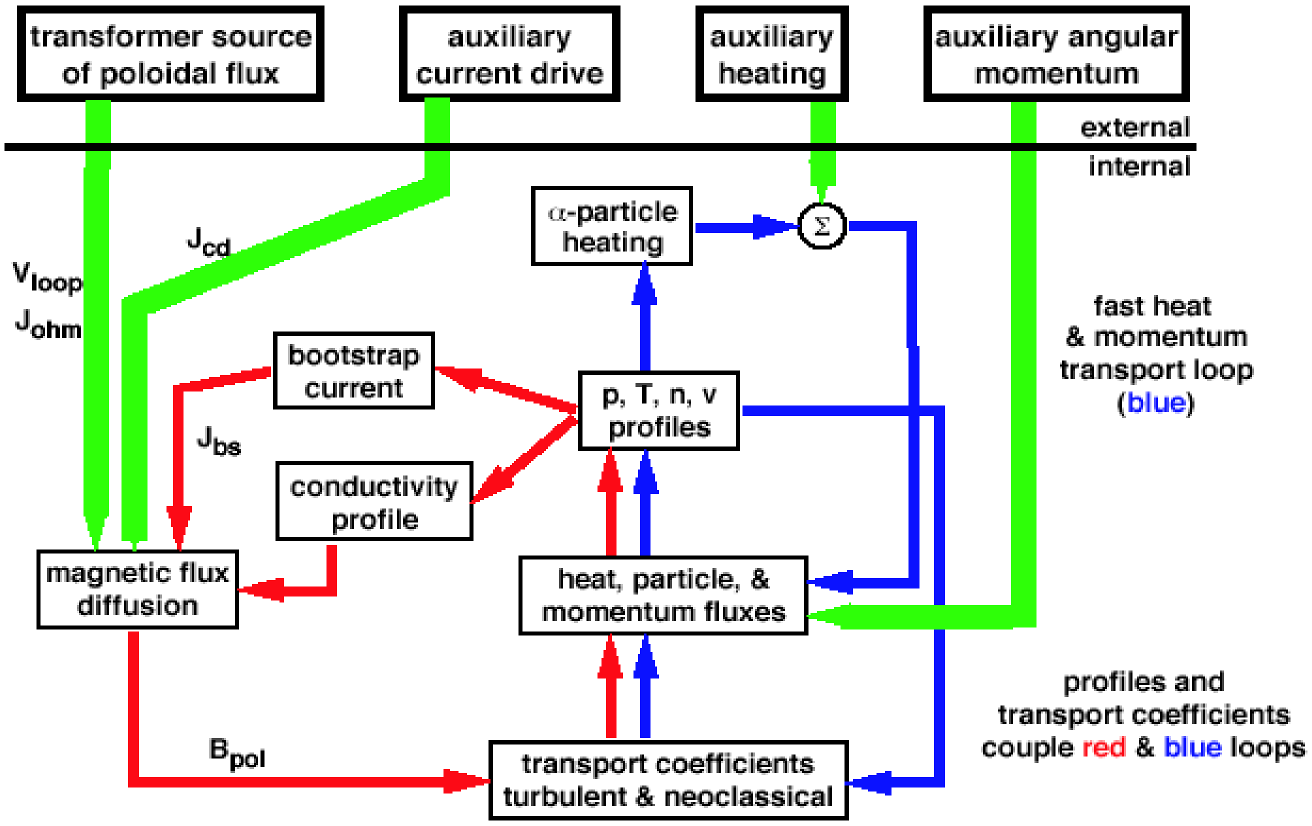
- Optimized pressure + current profiles
- q_{95}~5 (9MA) at high δ and high density
- $I_{non-inductive}/I_p$ ~100%, I_{boot}/I_p ~ 50%
- β_N~3, $H_{98(y,2)}$ ~1.5
- n_l~$7 \times 10^{19} m^{-3}$ (n/n_{Gw}~0.7)
- T_i/T_e ~ 1, at V_ϕ~100-150km/s
- $M_\phi = V_\phi / c_s$~0.2 , ρ* ~ 2×10^{-3} , ν* ~ 2×10^{-2}
- τ_D~3000s, τ/τ_E~1000, τ/τ_{res}~4

X. Litaudon, F. Crisanti and C. Challis (TFS2)

B. Green, PPCF 45 (2003) 687

Actuators and nonlinear couplings in present day experiments

TOKAMAK NONLINEAR TRANSPORT COUPLINGS



transformer source of poloidal flux

auxiliary current drive

auxiliary heating

auxiliary angular momentum

external

internal

α-particle heating

Σ

V_{loop}

J_{ohm}

J_{cd}

bootstrap current

J_{bs}

conductivity profile

p, T, n, v profiles

fast heat & momentum transport loop (blue)

magnetic flux diffusion

heat, particle, & momentum fluxes

B_{pol}

transport coefficients turbulent & neoclassical

profiles and transport coefficients couple red & blue loops

slow magnetic flux transport loop (red)

Figure from P. Politzer et al., ITPA meeting Lisbon 2004

Actuators and nonlinear couplings in a bootstrap-dominated steady state burning plasmas

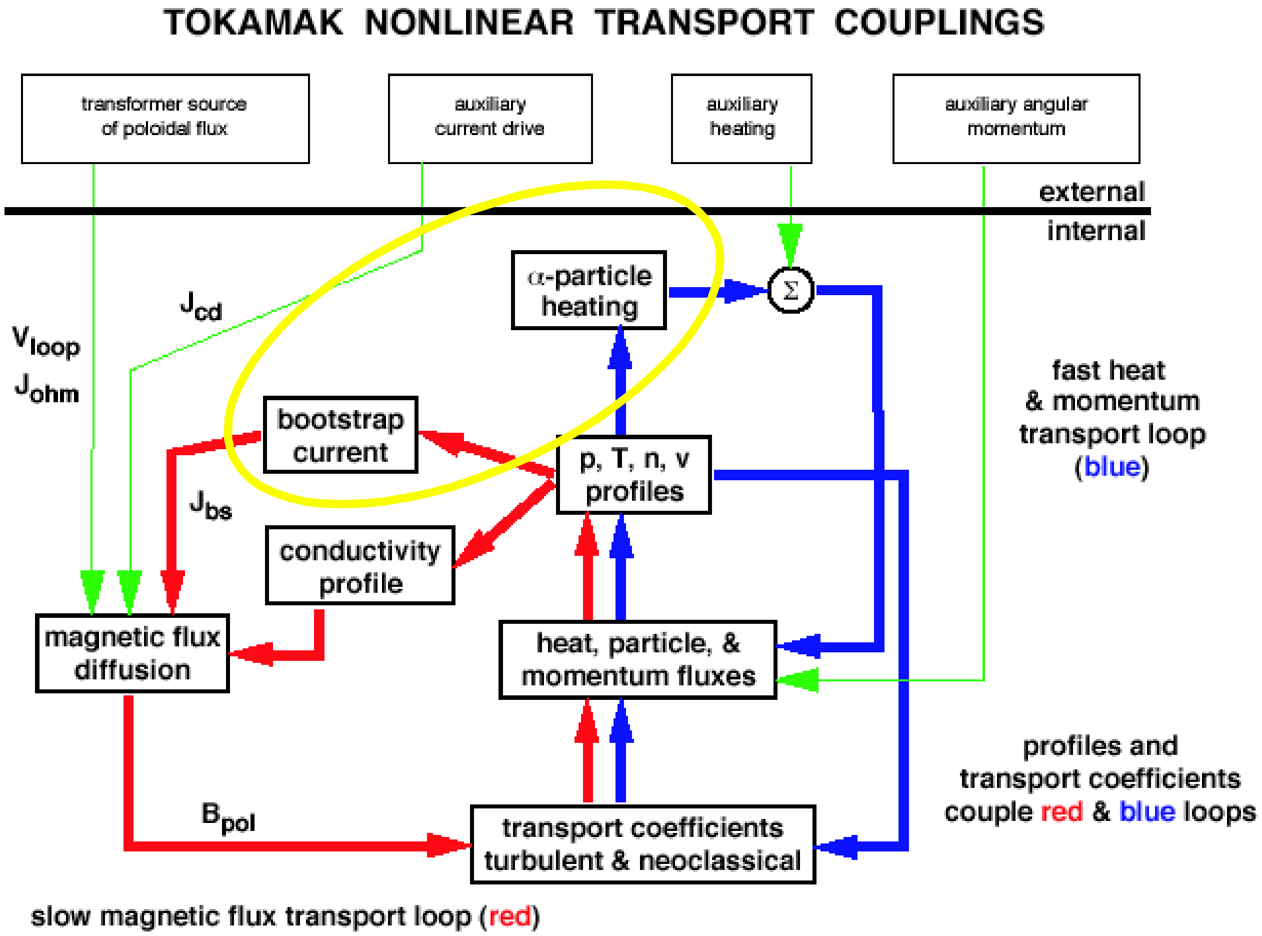
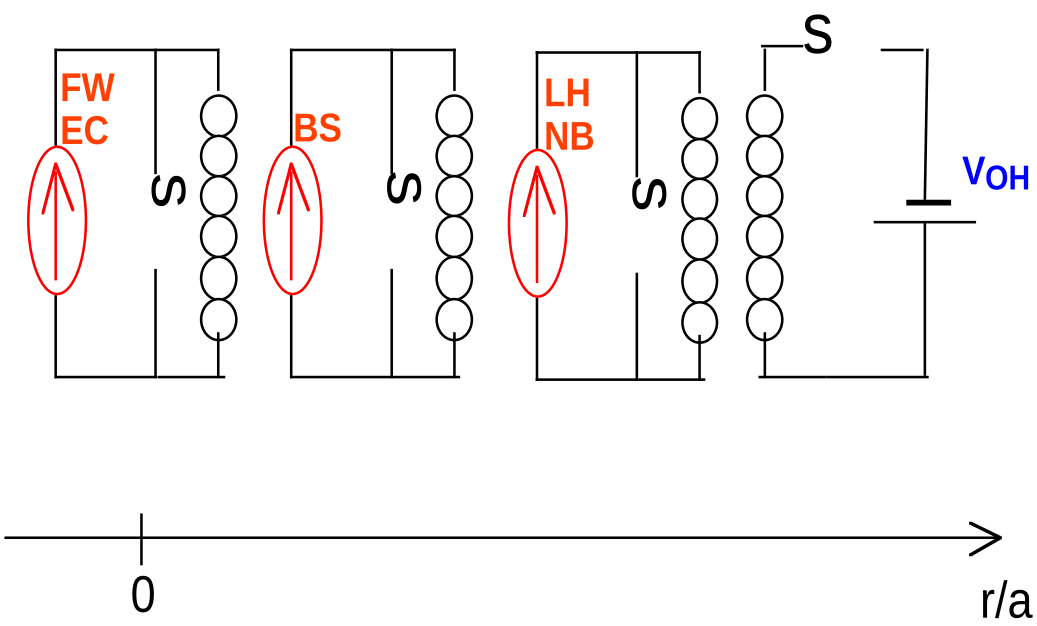


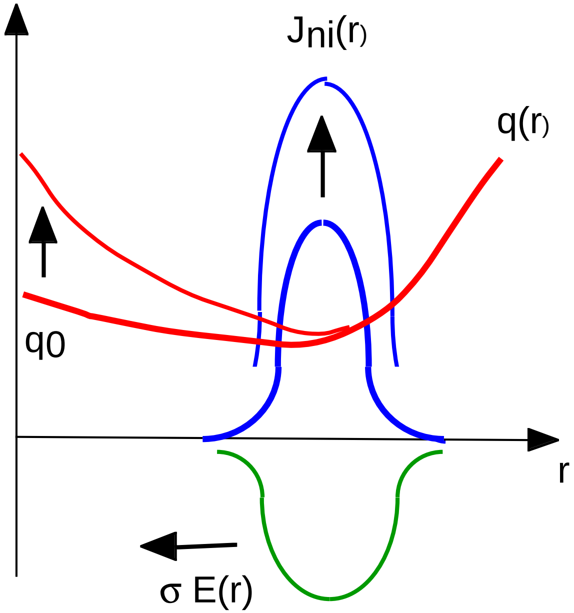
Figure from P. Politzer et al., ITPA meeting Lisbon 2004

From low-β to bootstrap-dominated burning plasmas

On the way to a bootstrap-dominated burning plasma,
the bootstrap current driven by the fusion power
acts as the primary circuit of a transformer

This can lead to the formation of a current hole
and requires integrated real-time profile control (magnetic/kinetic)





D. Moreau et al., Nucl. Fus. 39 (1999) 685

q-profile control in plasmas dominated by alphas + bootstrap current

The interplay between heating and current drive
in a plasma dominated by alpha heating + bootstrap current

can lead to uncontrollability : "frozen-in field"

Increase current drive power
⇒ Increase heating
⇒ Increase fusion rate and alpha heating
effect on temperature faster than effect on current
⇒ freezing of the current profile

Requires integrated burn (fueling) and profile control (H&CD)
(magnetic/kinetic - multiple time scales)

Requires experiments in simulated burning conditions (ICRH)
Requires experiments in DT plasmas (fuel/exhaust control)

Simulation of alpha-particle heating and burn control

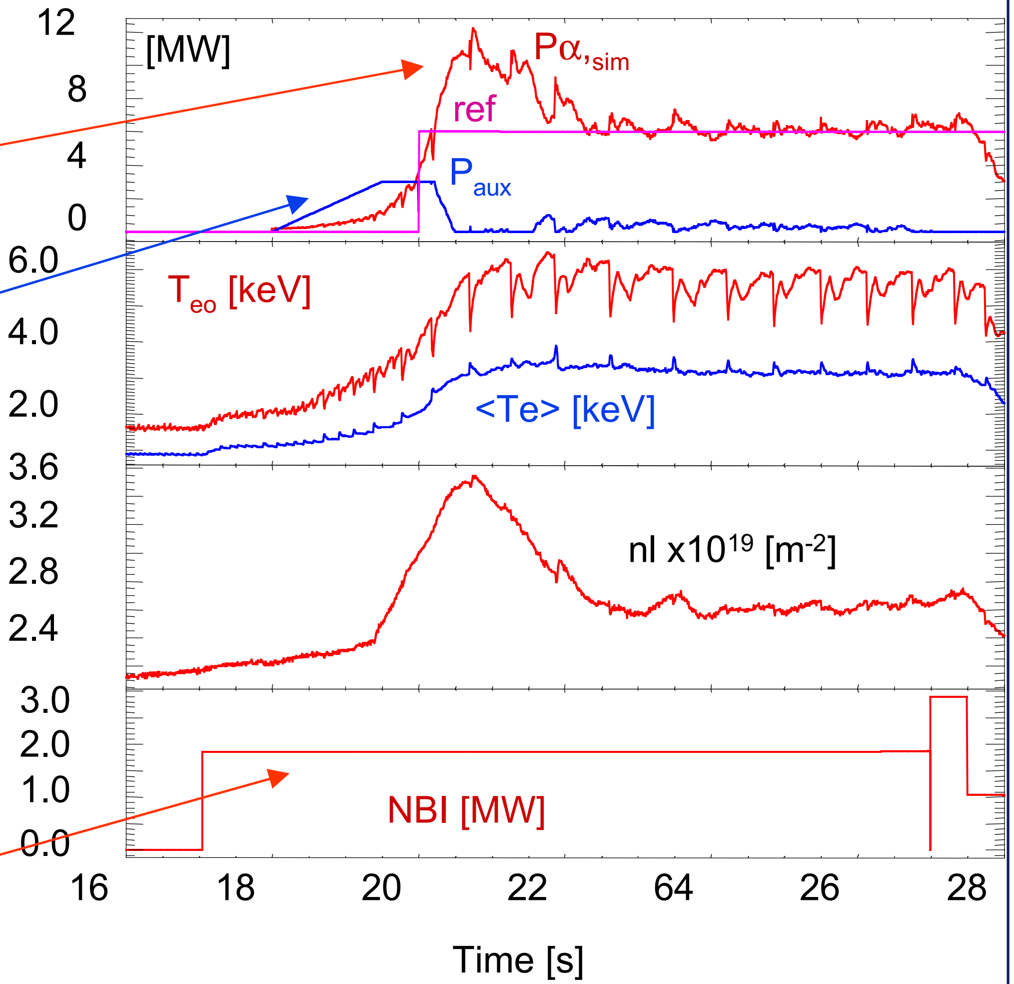
(Investigation of a thermal instability control in ITER relevant scenario)

ICRH to simulate α heating (90% absorbed on the electron channel)

ICRH as actuator to control P_α (to reach $P_\alpha = P_{ref}$)

ICRH waveform calculated from real-time measurements of n_e and T_e (whence → Pα)

NBI used to provide enough heating to reach H-mode



T.T.C. Jones et al, EPS 2001

q-PROFILE CONTROL ISSUES IN ADVANCED TOKAMAK BURNING PLASMAS

Alpha-power drives large bootstrap current

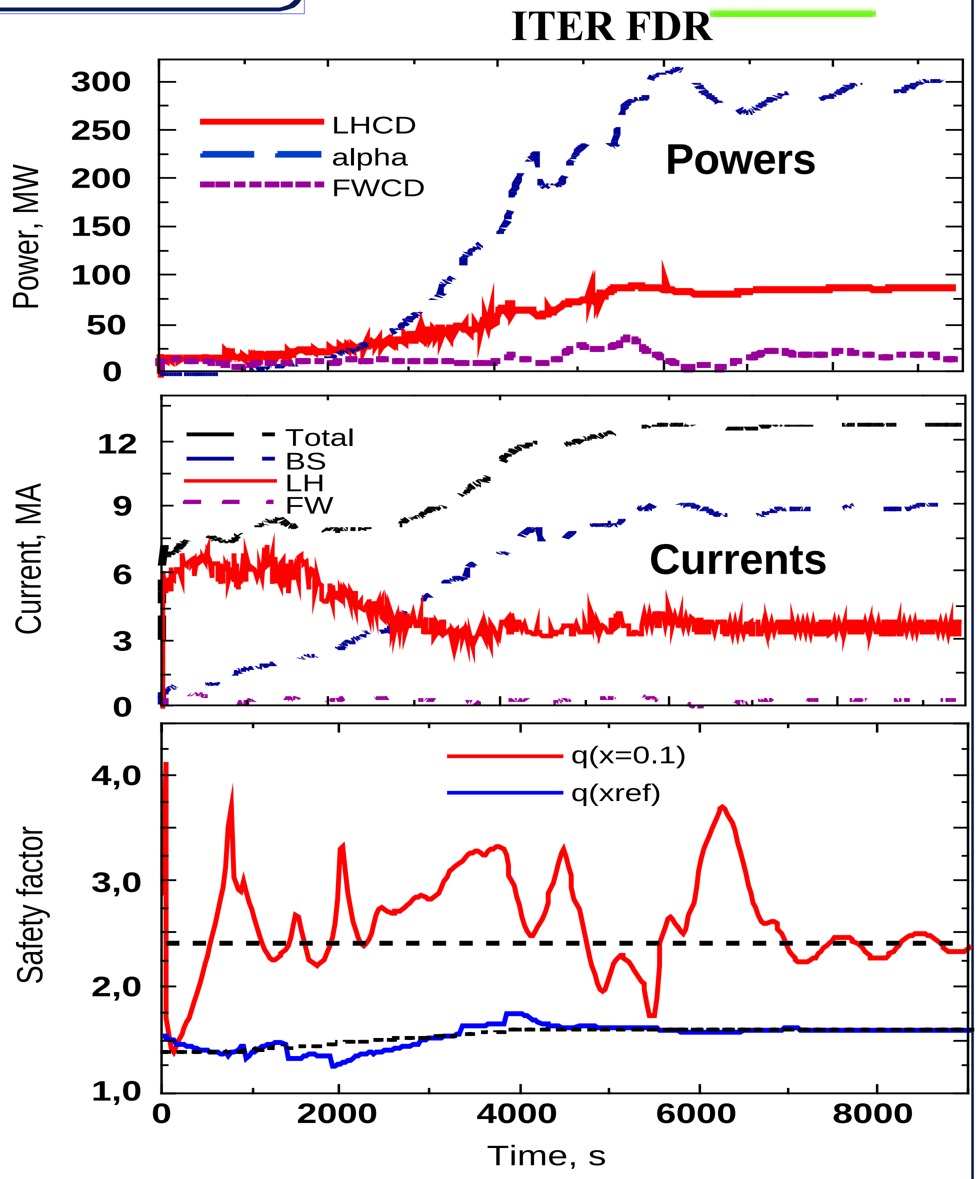
Excessive bootstrap current induces a current hole

Control with additional H&CD is difficult because of the interplay between heating and current drive

MAY REQUIRE ULTRA-SLOW FUSION POWER RAMP-UP

AND/OR

ACCURATE INTEGRATED CONTROL (MULTIPLE TIME SCALES)



D. Moreau et al., Nucl. Fus. 39 (1999) 685

What can an AT plasma controller achieve ?

Many profiles of parameters need to be controlled
with a rather limited number of actuators

Least square distributed parameter control
(trial basis functions + Galerkin scheme) :

Output profiles :

$$\mathcal{Y}(x,s)=\sum_{j=1}^{N}\mathcal{D}_j(x)\bullet\mathbf{Q}_j(s)+\text{residual}$$

Setpoint profiles :

$$\mathcal{Y}_{\text{setpoint}}(x)=\sum_{j=1}^{N}\mathcal{D}_j(x)\bullet\mathbf{Q}_{j,\text{setpoint}}+\text{residual}$$

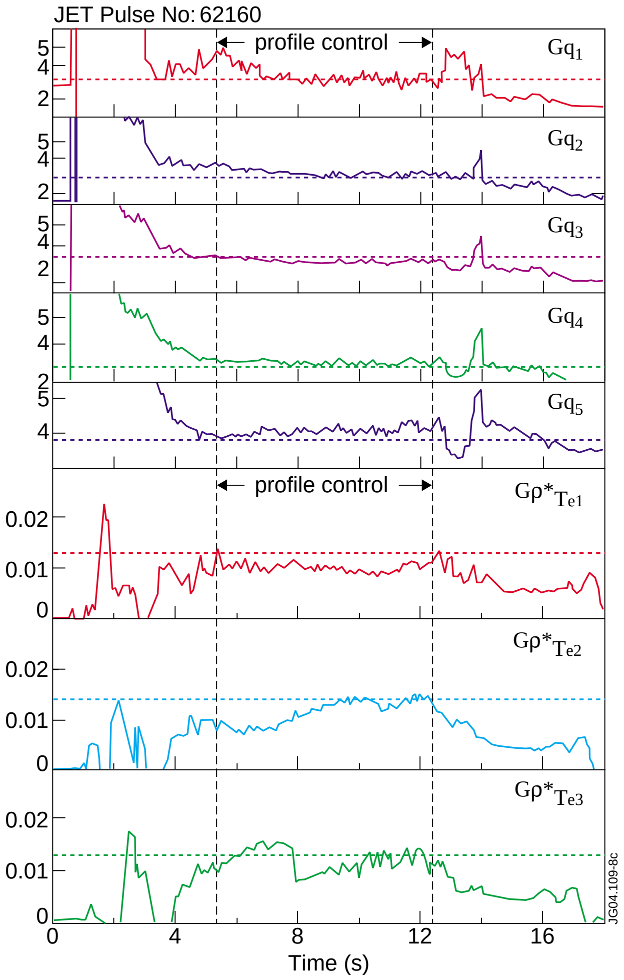
Design a controller to **minimize a least square quadratic form** :

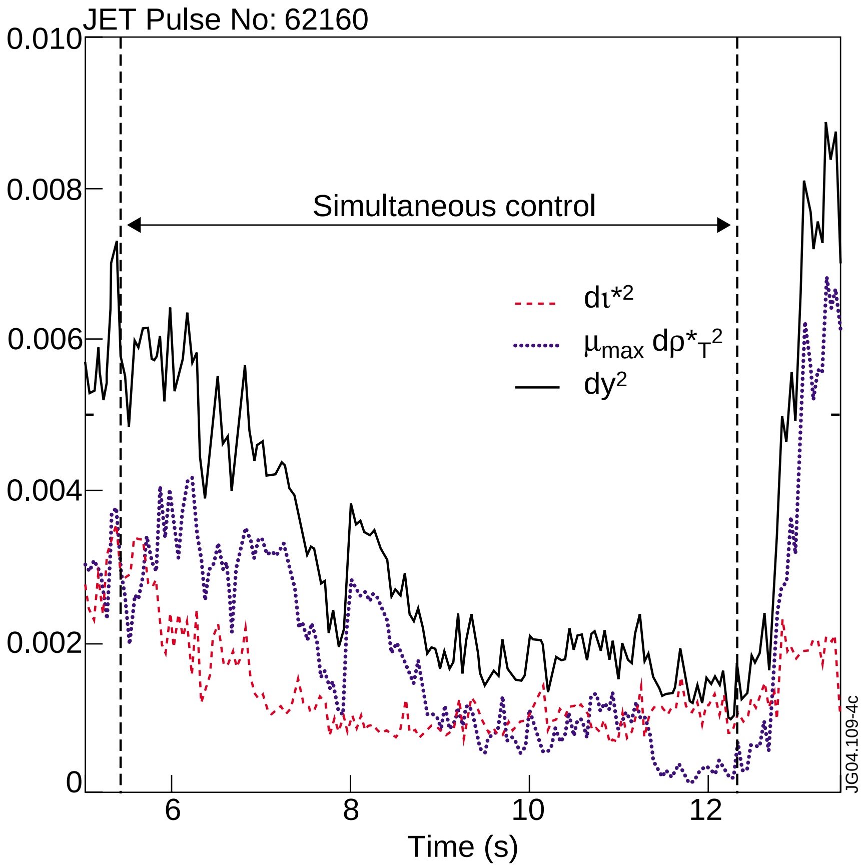
$$\int_0^1 \mu_1(x)\left[q(x)-q_{\text{setpoint}}(x)\right]^2 dx+\int_0^1 \mu_2(x)\left[\rho_T^*(x)-\rho_{T,\text{setpoint}}^*(x)\right]^2 dx$$

D. Moreau et al., Nucl. Fusion 43 (2003) 870

L. Laborde et al., PPCF 47 (2005) 155

Distributed-parameter control of q and ρ_{Te}*





Quadratic minimization

L. Laborde et al., PPCF 47 (2005) 155 **D. Mazon et al., EPS 2004** **D. Moreau et al. IAEA 2004**

Dynamic model identification using data from self-consistent JETTO simulations and from JETexperiments

Physics-based state-space model :

+ two-time-scale approximation

$\varepsilon = \tau_E / (\mu_0 \sigma_0 a^2)$

$$\begin{cases} \begin{pmatrix}\dot{X}\\ \epsilon \dot{Z}\end{pmatrix} = \mathbf{A}\begin{pmatrix}X\\ Z\end{pmatrix} + \mathbf{B}\,P \\ \begin{pmatrix}1/q\\ \rho^*_{Te}\end{pmatrix} = \mathbf{C}\begin{pmatrix}X\\ Z\end{pmatrix} + \mathbf{D}\,P \end{cases}$$

Relevant variables and couplings deduced from transport physics :

Inputs (U) : **H&CD powers : NBI, LHCD, ICRH**
surface voltage : VSU

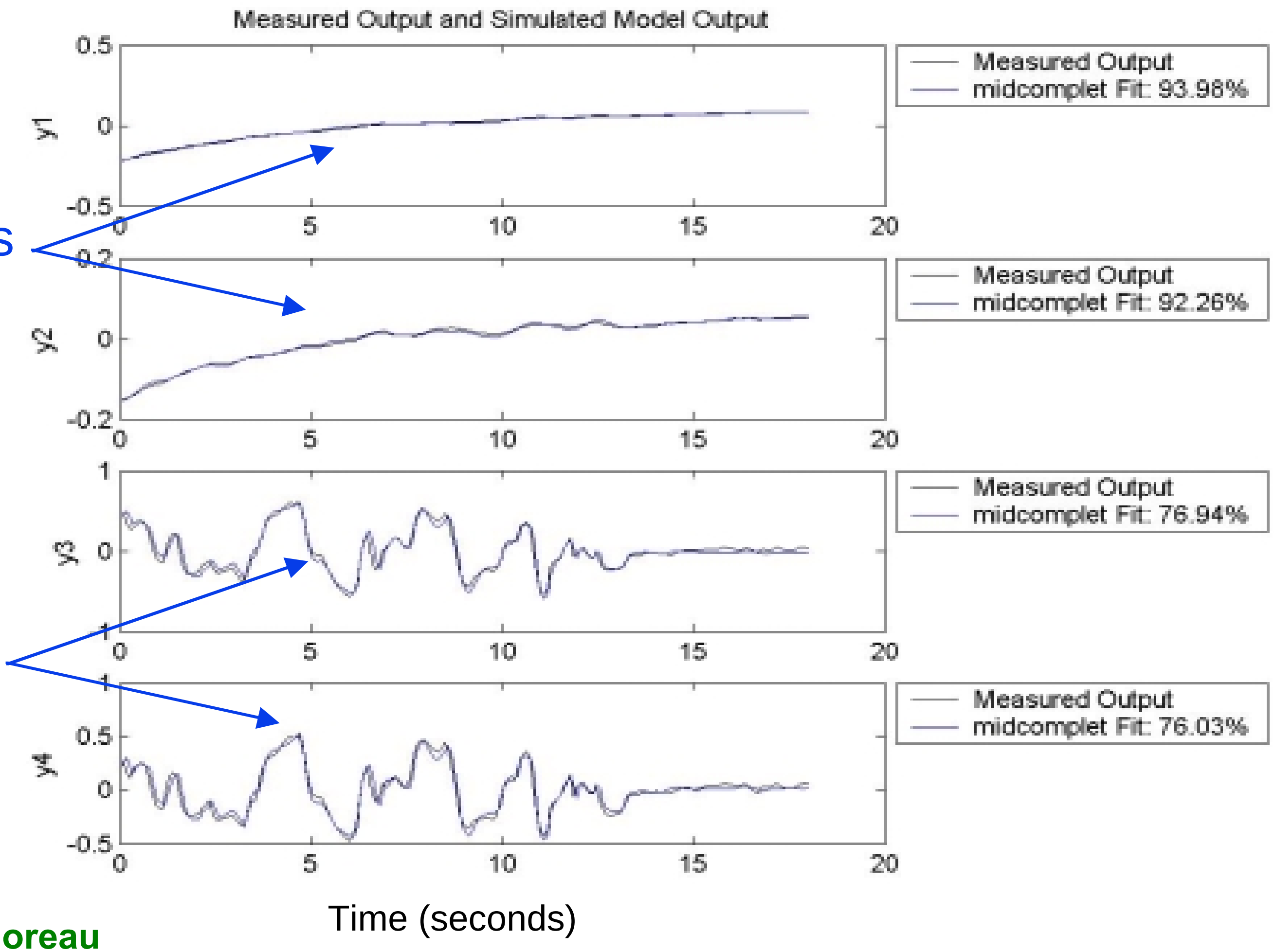
+

Disturbances (U) : **line-integrated densities : Ne_2, Ne_8**
+ other disturbances ...

State profiles (X) **: magnetic (flux ..) and kinetic (Te, .. later Ti, ne)**

Output profiles (Y) **: 1/q f(Te, ρ_{Te}*) (... later f(Ti, ρ_{Ti}*), P_{alpha} ...)**

Using the two-time-scale approximation as an initial guess for finding a grey box model (JETTO PPF 62527- 134)



slow variables

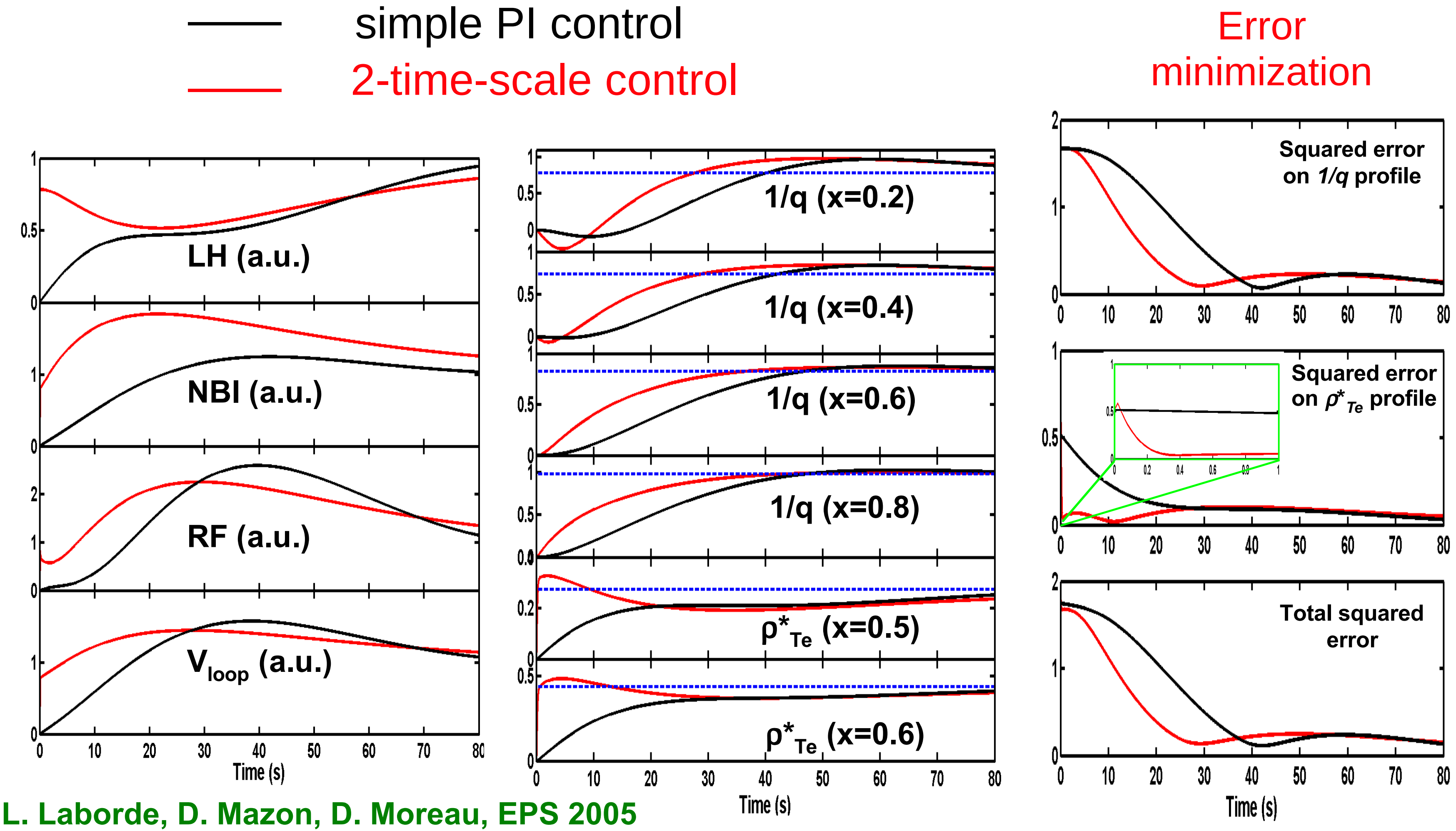
(magnetic)

fast variables

(kinetic)

V. Cordoliani, D. Moreau

Simulated closed-loop evolution of inputs (powers, V_{loop}) and outputs (1/q and ρ_T*)



L. Laborde, D. Mazon, D. Moreau, EPS 2005

First milestones towards AT scenario control on JET

1. 1999-2000 : Conceptual and modelling studies for controlling strongly coupled plasma profiles with a limited number of actuators :
   Safety factor profile (q)
   ITB : Dimensionless temperature or pressure gradient (ρ_{Te}*, ρ_{Ti}*, ρ_{P}*)
   + density, rotation ...

2. 2001-2002 : Control of the current profile :
   One actuator in the preheat phase : LHCD
   Three actuators in the performance phase : LHCD, NBI, ICRH

3. 2002-2004 : Extreme Shape Controller (XSC)

4. 2003-2004 : Simultaneous control of q(r) and ρ_{Te}*(r) with 3 actuators
   Modelling with JETTO and first successful experiments in JET

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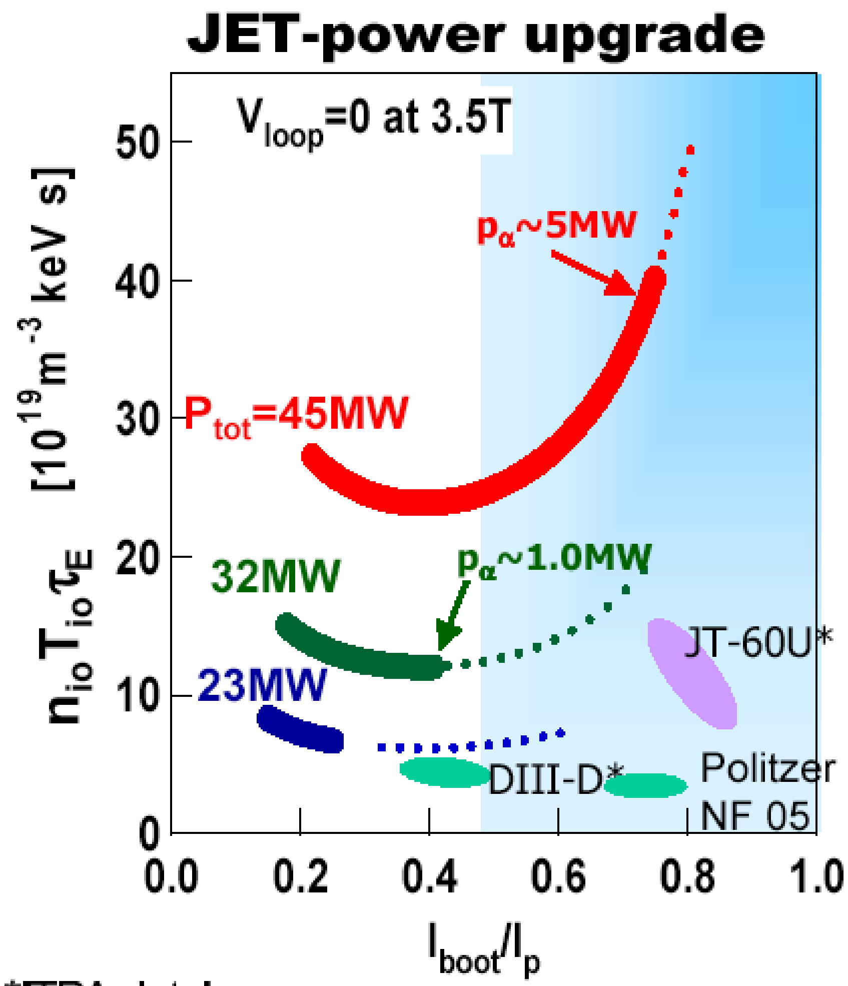
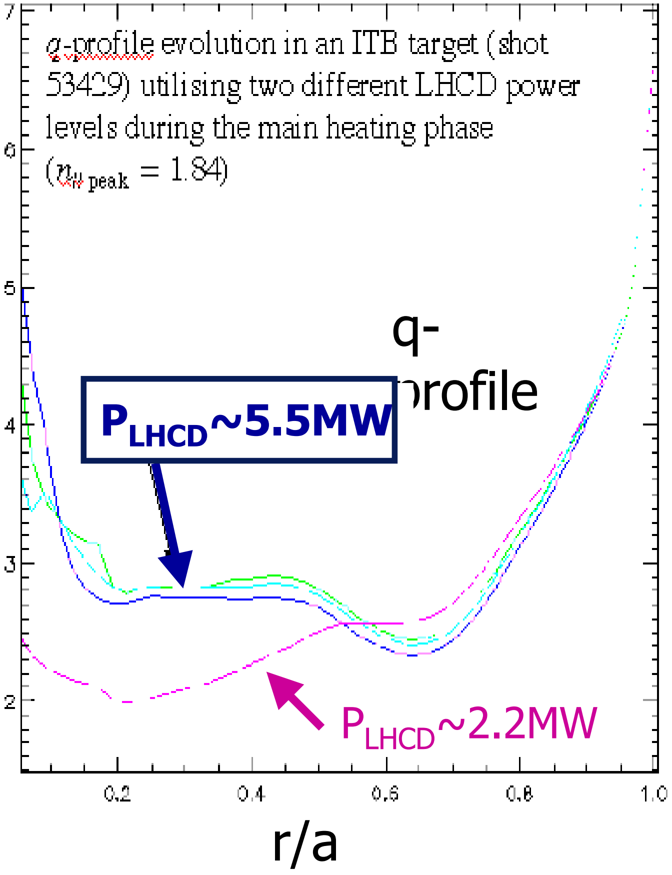
5. 2005-20... : Integrate shape, flux and 2-time-scale profile control in high-bootstrap non-inductive plasmas (profile control + XSC2 project).
   Simulate burning plasma conditions with ICRH + Real DT Experiment

What is needed to prepare the ITER AT scenarios on JET burning plasmas



*ITPA database

I_p~2.4MA; B_T~3.4T;
q_{95}~4.8, **n_l~2.5×10^{19}m^{-3}**


q-profile evolution in an ITB target (shot 53429) utilising two different LHCD power levels during the main heating phase ($n_{ll\,peak}$ = 1.84)

X. Litaudon, F. Crisanti and C. Challis, JET TFS2 Leaders

What is needed to prepare ITER AT scenarios on JET

Why AT burning plasma scenarios on JET ?

➔ reduce a heavy experimental development of an AT scenario on ITER

➔ clarify the "final" choice for the ITER-SS H&CD upgrade (up to 140 MW)

➔ investigate the integrated control requirements (profiles, flux, burn, wall ...)

Heating & CD power: P_{tot}~35-50MW **for integrated non-inductive scenario at high β and relevant q_{95} , T_i/T_e, M_ϕ, ρ∗ …**

(1) ITER-like ICRH antenna + A2 antennas (14 MW)

(2) NBI power upgrade (32 MW)

(3) LHCD launcher(s) for wall + α-heating compatible densities (>6MW PAM)

Fuelling systems: **reliable pellet fuelling (Tore Supra ~ 98%) to operate at higher core and edge density, decouple fuelling & heating, ELM mitigation**

Ergodic edge: **set of external magnetic coils for ELM suppression (DIII-D)**

Real-time equilibrium code + proper constraints **(EQUINOX-J + RT diagnostics)**

X. Litaudon, F. Crisanti and C. Challis, JET TFS2 Leaders

Conclusions

The application of AT scenarios to steady state burning plasmas will require the development of control techniques for **strongly coupled distributed-parameter systems** with a large number of output parameters but a limited number of actuators.

Investigations are in progress at JET to develop such control schemes

- **control of the plasma shape (eXtreme Shape Controller)**
- **of the safety factor profile, including q_{edge} (H&CD)**
- **of the temperature, density and rotation profiles (H&CD)**
- **of the primary flux consumption (XSC2 JET project)**

ITER perspective ... bootstrap-dominated regime (density/power)

Extend to an ICRH-simulated burn and to a D-T burning plasma

➔ Active M€ research needed in parallel with B€ ITER construction